

Long-range transport of Siberian biomass burning emissions and impact on surface ozone in western North America

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[1] During the summer of 2003, biomass fires burned a large area of Siberia, the largest in at least 10 years. We used the NRL Aerosol Analysis and Prediction System (NAAPS) model to forecast the transport of the smoke from these fires. Transport of these air masses to North America was confirmed by aircraft and surface observations. The fires resulted in enhancements in summer background CO and O₃ of 23–37 and 5–9 ppbv, respectively, at 10 sites in Alaska, Canada and the Pacific Northwest. From the area burned, we estimate that the Siberian fires generated 68 Tg of CO and 0.82 Tg of NO_x (as N). In addition, we show that the background O₃ enhancement contributed to an exceedance of the ozone air quality standard in the Pacific Northwest. These results show that regional air quality and health are linked to global processes, including climate, forest fires and long-range transport of pollutants.

INDEX TERMS: 0345 Atmospheric Composition and Structure: Pollution—urban and regional (0305); 0368 Atmospheric Composition and Structure: Troposphere—constituent transport and chemistry; 0365 Atmospheric Composition and Structure: Troposphere—composition and chemistry. **Citation:** Jaffe, D., I. Bertsch, L. Jaeglé, P. Novelli, J. S. Reid, H. Tanimoto, R. Vingarzan, and D. L. Westphal (2004), Long-range transport of Siberian biomass burning emissions and impact on surface ozone in western North America, *Geophys. Res. Lett.*, 31, L16106, doi:10.1029/2004GL020093.

1. Introduction

[2] Previous studies have identified trans-Pacific transport of atmospheric pollutants during spring [Jaffe *et al.*, 2003a, 2003b; Fiore *et al.*, 2002]. Occasionally these pollutants are transported downward and result in substantial concentrations at the surface [Jaffe *et al.*, 2003a]. However we know little about how this phenomenon contributes to regional air quality. During summer, large-scale biomass burning in boreal forests can contribute to

regional and hemispheric air pollution [McKeen *et al.*, 2002; Wotawa *et al.*, 2001].

[3] During the summer of 2003 we conducted vertical profiles near the coast of Washington state to obtain information on the background levels of CO, O₃ and aerosol light scattering between 0 and 6 km above sea level (asl). The methods used in the summer of 2003, were nearly identical to our previous measurements conducted in the previous few years [Bertschi *et al.*, 2004, and references therein]. The results of our summer 2003 aircraft measurements are described in a separate paper (I. Bertsch and D. Jaffe, Aircraft observations of plumes from Asian boreal fires during 2003, submitted to *Journal of Geophysical Research*, 2004, hereinafter referred to as Bertsch and Jaffe, submitted manuscript, 2004). In the present paper, we show how large biomass fires in Siberia during 2003 impacted both CO and O₃ over a wide region of western North America and contributed to an exceedance of the O₃ air quality standard in the Pacific Northwest.

2. Experimental

[4] We used results from the Naval Research Laboratory Aerosol Analysis and Prediction System (NAAPS, <http://www.nrlmry.navy.mil/aerosol/>) to identify possible episodes of long-range transport. The NAAPS model has recently been modified to incorporate real-time observations of biomass burning based on the joint Navy/NASA/NOAA Fire Locating and Modeling of Burning Emissions system (FLAMBE, <http://www.nrlmry.navy.mil/flambe/>) [Reid *et al.*, 2004]. For smoke fluxes in Siberia, twice daily MODIS fire products at ~10:30 and 14:00 local time were used, along with the methods described by Reid *et al.* [2004].

[5] We used O₃ and CO data from 10 rural and background sites in the Northwestern U.S., British Columbia and Alaska¹. We also used the GEOS-CHEM model, which is a global 3-D chemical transport model driven by assimilated meteorological data from Goddard Earth Observing System (GEOS) of the NASA Global Modeling and Assimilation Office. Tropospheric ozone-NO_x-hydrocarbon-sulfur chemistry in the model includes 31 transported tracers, 120 chemical species, and over 200 reactions, including treatment of aerosols [Bey *et al.*, 2001; Martin *et al.*, 2003]. The simulations presented here use GEOS-CHEM model version 5.03 with a horizontal resolution of 4 degrees latitude by 5 degrees longitude and 30 vertical layers.

[6] For this work, we conducted a reference simulation using GEOS-CHEM, with a climatological inventory of biomass burned [Lobert *et al.*, 1999; Duncan *et al.*, 2003]

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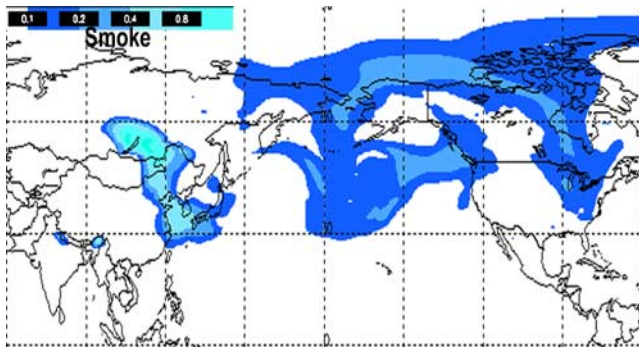


Figure 1. NAAPS model aerosol optical depth (AOD) for June 2, 2003, 12 GMT for the smoke component. The enhanced AOD over western North America originated from the Siberia fires located near 50°N 110°E.

with emission factors described by *Staudt et al.* [2003], yielding CO and NO_x emissions over Asiatic Russia (40–90N; 60–180E) of 17 Tg CO and 0.21 Tg NO_x (as N). A comparison of this reference simulation to surface CO observations throughout the North Pacific for 2001 showed no significant bias [*Liang et al.*, 2004]. We also conducted a simulation with enhanced biomass burning emissions for the 2003 fire season using data from the Global Fire Monitoring Center (GFMC, <http://www.fire.uni-freiburg.de/>). Using the GFMC estimate of 18.9 million hectares burned in 2003, average fuel consumption of 30 tons/hectare and emission factors of 120 g CO/kg fuel burned and 1.4 g N/kg fuel burned, we calculate CO and NO_x emissions from the fires of 68 Tg and 0.82 Tg (as N), respectively, or 3.9 times the climatological emissions. While there is some uncertainty in these values, the values we have used are consistent with other reports for high latitude biomass fires [e.g., *Kasischke and Bruhwiler*, 2002; *Cofer et al.*, 1998; *Goode et al.*, 2000, and references therein].

[7] To allocate the emissions, we used the spatial distribution of monthly fires detected by MODIS/TERRA between May and September 2003 and vertically distribute them between 1.5 and 4.5 km altitude [*Lavoue et al.*, 2000]. Because assimilated meteorological fields for 2003 were not available at the time of this work, we used meteorological fields for the spring-summer of 2001, which was climatologically similar to 2003. While this prevents us from making a direct day-by-day comparison with the measurements, it is unlikely to influence the mean summer results shown below.

3. Results

[8] Satellite images and model forecasts from NAAPS for May–August 2003 suggested substantial emissions and trans-Pacific transport of smoke from the large fires burning in Siberia at that time. Figure 1 shows that the NAAPS model predicted aerosol optical depths of 0.1–0.4 over the U.S. Pacific Northwest (PNW) and north-eastern Pacific on June 2, 2003 due to smoke from the Siberian fires. On the same day we measured substantial concentrations of CO, O₃ and aerosols during our aircraft vertical profiles, in westerly flow off the coast of Washington state. This confirmed the arrival of the Siberian smoke to the North American lower troposphere. Back-trajectories, calculated with the

NOAA-Hysplit model, corroborate that this air mass passed over Siberia, in the region where the fires were burning. Nonetheless, because this air mass passed over industrial as well as some desert regions during transport, it is likely that industrial pollutants and mineral dust were also present. Transport of smoke from the Siberia fires was identified on several other occasions during the summer of 2003, from both the aircraft observations and the NAAPS model (*Bertschi and Jaffe*, submitted manuscript, 2004).

[9] The 2003 Russian area burned, 18.9 million hectares, was more than twice the annual average for Russian fires between 1996 and 2003. Based on MODIS fire hotspot data, the Russian forest fires near Lake Baikal in May were the largest and most intense episodes seen in Siberia since MODIS began collecting such data in 2000. So while there is some uncertainty in these burned areas, the estimated area burned in 2003 was comparable to, or more likely larger than, the 14.4 million ha, that was reported for Asian boreal fires in 1987 [*Cahoon et al.*, 1991] and the 17.9 million ha that was reported for all boreal regions in 1998 [*Kasischke and Bruhwiler*, 2002]. However it should be noted that the area burned may not directly correlate with emissions, since the fires can vary from flaming to smoldering and burn over a variety of ecosystem types.

[10] In Figure 2 we show the annual area of Russian biomass fires since 1996 (GFMC data), along with summer-mean O₃ and CO concentrations from 8 sites in western North America. Data from all sites, along with a map showing the locations, is given in the supplementary electronic section. The annual areas burned, shown in Figure 2, have an uncertainty of approximately 20% (*E. Kasischke*, personal communication, 2003). Because of the large number of locations considered, Figure 2 shows the sites grouped by region, but the pattern is identical if the data from individual sites is considered. Two sites with shorter

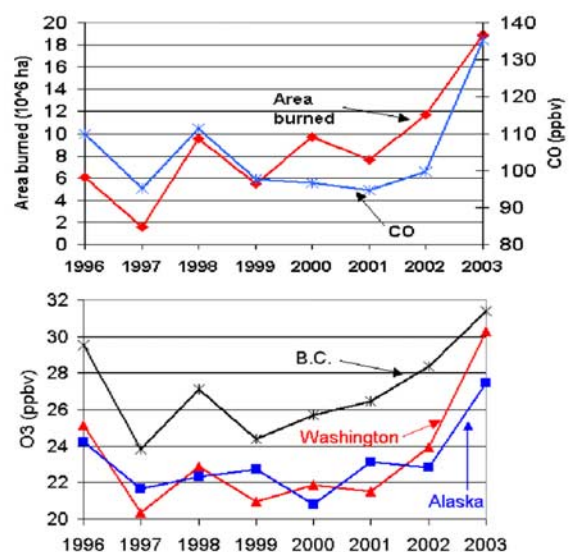


Figure 2. Total Russian area burned (GFMC data) and mean summer mixing ratios (June, July, August) vs year for sites in Alaska, British Columbia and Washington. (top): Burned area and Alaskan CO (Barrow, Cold Bay and Shemya). (bottom): Alaskan O₃ (Denali N.P. and Barrow), British Columbia O₃ (Saturna Island) and Washington O₃ (Enumclaw, Mt. Rainier and North Cascades National Park).

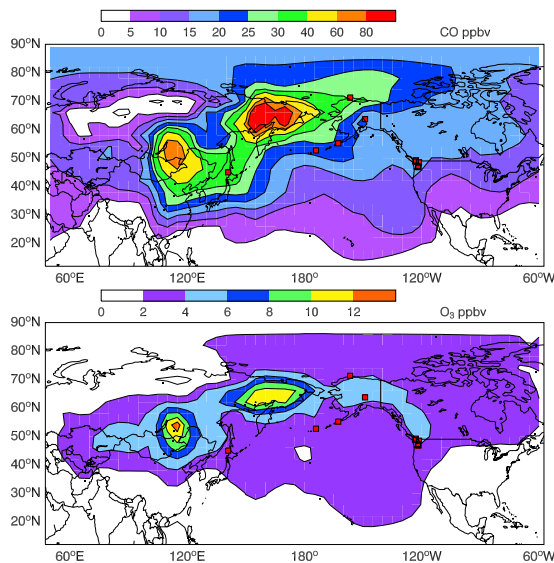


Figure 3. GEOS-CHEM model results showing the mean enhancements in surface concentrations for June 1–August 31 from the 2003 Russian fires, relative to a reference simulation with climatological biomass burning emissions for CO (top) and O₃ (bottom). Red dots show the locations of observations given in Figure 2 and in the electronic supplement.

data records (6 years or less) were not included in Figure 2, but are included in the supplementary data. At every site examined except one, the summer of 2003 had the highest mean O₃ and CO mixing ratios. At Barrow the summer of 2003 had the highest mean CO mixing ratio ever seen, but the third highest O₃ value out of 31 years of observations, only 1987 and 1991 had higher mean summer O₃ values. Regressions of the seasonal mean O₃ and CO mixing ratios with Russian area burned are statistically significant at all sites ($p = 0.01$ – 0.10 depending on site). These regressions indicate that the area of Russian biomass burning explains between 42–86% of the interannual variations in seasonal mean CO and O₃ for the sites considered.

[11] For the May–September 2003 period, the largest number of fires occurred in May (45%), centered near 54°N 115°E, followed by August (24%), centered near 64°N 152°E. Data from Rishiri Island, Japan (provided in the electronic supplement), clearly show the influence from the large fires burning in early summer. The May–June average CO and O₃ concentrations at Rishiri Island in 2003 were the highest in the data record, being enhanced by 26 and 10%, respectively, over the 6-year mean. In July, the Rishiri site was largely missed by these emissions, which were now further north and west.

[12] Figure 3 shows the CO and O₃ enhancements calculated by the GEOS-CHEM model for a simulation with the 2003 Russian biomass burning emissions compared to a simulation with climatological biomass burning emissions. The model simulation calculates enhancements in CO of 20–35 ppbv for sites in Alaska, very similar to what is observed (23–37 ppbv). For O₃, the model calculates enhancements of 2–6 ppbv, again similar to the observations (5–9 ppbv). The GEOS-CHEM results confirm that the Russian fires had a significant impact on CO

and O₃ levels in western North America, consistent with the observations.

[13] Because O₃ is an important summertime air pollutant, we wish to evaluate whether the 2003 Russian fires, had an influence on urban air quality in North America. The June 2, 2003 episode of long-range transport arrived to the Pacific Northwest at a relatively low altitude. Between May 27th and June 9th, surface monitoring sites in Washington state and British Columbia, including Tahoma Woods, Jackson Visitor's Center, Saturna Island and the North Cascades National Park, all had elevated O₃, compared to the long-term average for May and June. The average enhancement at these sites for June 1–6th, 2003 was between 9 and 17 ppbv, depending on the site. While aircraft data are only available for June 2nd, the surface monitoring data suggest that an influence from the Siberian fires was present throughout this time period.

[14] On June 6th, 2003, the O₃ monitoring site at Enumclaw, Washington, a rural location approximately 50 km south-southeast of Seattle, reported an 8-hour average O₃ mixing ratio of 96 ppbv, which exceeds the U.S. air quality standard. While the primary cause for this high O₃ was local emissions and photochemistry, combined with poor dispersion conditions, emissions from the Russian fires may have also contributed. To examine this hypothesis, we used temperature as a surrogate indicator of local O₃ production [National Research Council (NRC), 1991]. Figure 4 shows the daily maximum 8-hour O₃ mixing ratio for the Enumclaw site vs. temperature for late-spring-early fall data from 1996–2003. The positive correlation between O₃ and temperature reflects multiple factors including increased reaction rates, increased solar insolation and decreased ventilation [NRC, 1991]. For the Enumclaw data, a statistically significant relationship is found between temperature and O₃ above 20°C. Superimposed on Figure 4 are the observations from June 1–6, 2003. These data have higher O₃ than indicated by the temperature relationship, and therefore suggest additional O₃ from a non-local source. From the O₃-temperature regression, shown in Figure 4, we estimate the Siberian fires contributed approximately 15 ppbv to the 96 ppbv observed on June 6th, based on the difference between the regression line and the June 6th observations. Using the same data, but taking a different

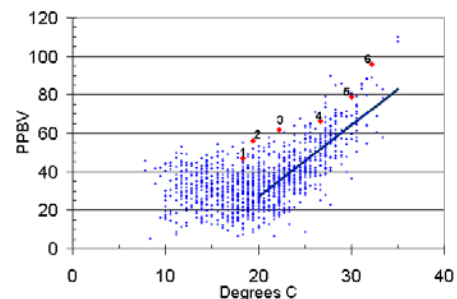


Figure 4. Plot of Enumclaw, Washington daily maximum 8 hour mean O₃ mixing ratio vs maximum daily temperature from the Seattle-Tacoma International Airport. Data are from May–September for the years 1996 through 2003. Data from June 1–6, 2003 are shown with red points and the numbers 1–6. The regression line is statistically significant starting at 20°C.

approach, we select out only those days with a maximum temperature greater than 31°C. This yields 21 points (days) with a mean maximum temperature of 32.3±0.5°C (95% confidence interval) and a mean 8-hour O₃ mixing ratio of 79±7 ppbv (95% confidence interval). So while the June 6th, 2003 maximum temperature of 32.2°C is close to the mean of this distribution, the 8-hour O₃ average of 96 ppbv is a significant outlier. While these estimates of the enhancement due to long-range transport for June 6th must be considered as approximate, they are consistent with the enhancements of 9–17 ppbv seen at other sites in Washington and B.C. for the June 1–6th period.

[15] *Fiore et al.* [2002] used a global model to calculate the influence from long-range transport on background O₃ in the U.S. They found that anthropogenic sources in Europe and Asia contribute 4–7 ppbv of O₃ at surface sites in the U.S. during summer. However not included in this is the contribution from large-scale episodic boreal fires. Our results show that the contribution from Siberian fires, in some years, adds significantly to these background levels.

[16] Large-scale influence from biomass fires has been reported previously [*Wotawa et al.*, 2001; *Tanimoto et al.*, 2000; *McKeen et al.*, 2002]. Our results show that Russian biomass burning emissions can contribute to elevated O₃ over western North America and that the burned area helps explain interannual variations in background O₃ mixing ratios. The summer of 2003 saw the largest amount of Siberian biomass burning in the recent past and this was likely a contributor to the elevated O₃ seen at numerous sites in western North America. Additionally, for the first time, we show that long-range transport of these emissions contributed to an exceedance of the air quality standard. Given the likelihood of increasing boreal fires in a warmer world [*Kasischke et al.*, 1995; *Wotton et al.*, 2003], these results suggest a linkage between climate change, boreal forest fires, long-range transport of air pollutants and human health. Thus changes in the boreal regions could have important implications for changes in background O₃ along the west coast of North America [e.g., *Jaffe et al.*, 2003c].

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Supplementary electronic materials

Surface data sources

Table 1 lists details on the 11 surface sites (10 in North America, 1 in Japan) used in our analysis and provides annual summer mean data. Figure 1 is a map showing the locations of these sites. Surface O₃ observations are made routinely at 9 of these sites, and CO is measured at 3. Only one background site, Barrow Alaska, has long-term measurements of both CO and O₃. At all sites, O₃ is measured using a standard UV absorption monitor. Observations by the National Park Service are described at <http://www2.nature.nps.gov>. The observations of O₃ by NOAA-CMDL at the Barrow site are described in Oltmans and Levy [1994] and available on-line at www.cmdl.noaa.gov. All O₃ measurements are believed to be accurate to 3%.

Observations of CO by NOAA-CMDL at the three Alaskan sites are described in Novelli et al. [2003]. Observations of CO and O₃ at Rishiri Island, Japan are described by Tanimoto et al. [2000]. Observations of O₃ in British Columbia are made by the Canadian Air and Precipitation Monitoring Network (Saturna Island) and the British Columbia Ministry of Water, Lands and Air Protection (Victoria). Details on the monitoring protocols are given at <http://www.msc.ec.gc.ca/capmon/>

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Table 1. Information and annual summer mean (June, July and August) concentrations from each site. O₃ and CO data are given in ppbv.

Site	Enumclaw, Wash.	Tahoma Woods, Wash	Jackson Visitor's Center, Wash.	North Cascades National Park, Wash	Saturna Island, BC	Victoria, B.C.
Location	47.1 N 121.9 W 394 m	46.8 N 122.1 W 423 m	46.8 N 121.7 W 1650 m asl	48.5 N 121.4 W 109 m asl	48.8 N 123.1 W 178 m asl	48.4 N 123.4 W 22 m asl
Type	Rural	Rural	Remote	Remote	Rural	Urban
Parameter	O ₃	O ₃	O ₃	O ₃	O ₃	O ₃
Data source	Wash. Ecology/ PSCAA	NPS/Wash. Ecology/ PSCAA	NPS/Wash. Ecology/ PSCAA	NPS	Env. Canada	Env. Canada
1990		28.8				
1991		28.8			26.3	
1992		26.0			27.2	
1993		20.6			20.4	
1994		28.0			27.4	
1995		24.6			24.9	
1996	23.3	29.1		22.9	29.5	
1997	21.6	24.1		15.4	23.8	
1998	27.5	25.3		15.9	27.1	16.7
1999	23.1	22.8		17.0	24.4	15.8
2000	24.1	23.8	35.4	17.7	25.7	15.3
2001	22.2	24.0	36.1	18.3	26.5	15.2

2002	26.6	25.8	37.7	19.4	28.4	17.2
2003	34.0	31.2	44.8	25.7	31.4	19.4
Mean	25.3	25.9	38.5	19.0	26.4	16.6

Site	Denali National Park, Ak	Barrow, Ak ¹	Barrow, Ak	Cold Bay, Ak	Shemya, Ak	Rishiri Island, Japan ³	Rishiri Island, Japan ³
Location/alt.	63.7 N 149.0 W 661 m asl	71.3 N 156.6 W 11 m asl	71.3 N 156.6 W 11 m asl	55.2 N 162.7 W 25 m asl	52.7 N 174.1 W 40 m asl	45.1 N 141.1 E 35 m asl	45.1 N 141.1 E 35 m asl
Type	Remote	Remote	Remote	Remote	Remote	Remote	Remote
Parameter	O ₃	O ₃	CO	CO	CO	CO	O ₃
Data source	NPS	NOAA-CMDL	NOAA-CMDL	NOAA-CMDL	NOAA-CMDL	NIES-AED	NIES-AED
1988	25.4	23.9	90.9				
1989	23.7	21.7	102.7				
1990	23.4	23.4	102.6				
1991	23.8	27.1	99.5				
1992	22.9	18.9	102.0	102.9	110.6		
1993	23.5	19.7	90.3	91.3	97.5		
1994	22.2	23.0	101.2	103.2	104.0		
1995	20.8	24.4	95.9	94.5	98.9		
1996	23.4	25.1	101.2	110.9	117.3		
1997	23.1	20.2	91.3	93.6	101.1		
1998	23.8	20.8	108.0	112.1	114.3	163.3	41.6
1999	25.4	20.1	96.2	97.4	99.7	167.9	45.5

2000	21.2	20.5	92.3	95.3	102.2	168.6	42.4
2001	24.6	21.6	92.7	93.9	97.1	160.9	41.9
2002	24.4	21.3	97.6	98.8	102.7	139.2	38.6
2003	29.2	25.7	122.4	138.9	144.6	213.4	47.1
Mean	23.8	22.6	99.2	102.7	107.5	168.9	42.8

¹ For Barrow, surface ozone data go back to 1973. Additional data can be obtained from: <http://www.cmdl.noaa.gov>

² Because of a short data record, data from the Jackson Visitor's Center and Victoria, B.C. were not used in Figure 3.

³ Rishiri Island means are given for May-June, since very little impact from the fires was seen at this site in July.

Figure 5-Supplement section. Map showing data sites used in this work. The sites are Rishiri Island (RIS), Shemya (SHM), Cold Bay (CBA), Barrow (BRW), Denali National Park (DNP), Victoria (VIC), Saturna Island (SAT), Tahoma Woods (TWD), Enumclaw (ENM), Jackson Visitor's Center (JVC) and North Cascades National Park (NCP).

